All-Electric vs Conventional Aircraft: The Production/Operational Aspects

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The emergence of an all-electric airplane in the role of an energy efficient transport is described in relation to the increasing fuel problems which are impacting on the economic viability of the aerospace industry. The paper reviews the all-electric airplane for its impact upon the design/implementation of the aircraft systems, the advanced technology engines, the aircraft's ground-logistic support, and the operational/producibility aspects of these advanced transport aircraft. The simplification of engine design and the prospective improvements in its specific fuel consumption are highlighted along with the overall simplification of the aircraft production aspects of the all-electric airplane.

Introduction

ALL-ELECTRIC aircraft relate to air transports where the conventional aircraft accessories, or power components, are replaced by one or more electric generators with the objective of providing a more simple and reliable secondary power system. Pertinent to this, recent NASA/Lockheed studies[1,2] have identified the all-electric airplane as an energy efficient transport and one that offers the benefits of eliminating such labor-intensive systems as high-pressure hydraulics, engine bleed air, pneumatics and the nonelectric engine-start systems. Also, there is a significant reduction in the ground maintenance/logistic support, when the ground equipment associated with the multiple power sources is replaced with electric power. These latter benefits were projected but not quantified in the NASA/Lockheed studies. Costs are an important aspect of the technology, and Fig. 1 is a pie-section of their breakdown in a typical aircraft.

Turbine Engine Technology

While propulsion is the primary role of the modern engine, its historic secondary role has been to provide pressurized air and mechanical drives for the accessory power components. These accessory drive provisions have not only complicated the production design of the engine, but the gearbox has often created an undesirable ballooning of the nacelle. Mainly, however, it is the practice of bleeding the high-bypass ratio engine that has become an aspect of major concern because of the thrust/specific fuel consumption (SFC) penalties. For example, on a 5 h flight, the cruise thrust fuel penalty (for a three-engine commercial transport) is about 2200 lb for 6 lb/s of bleed vs 668 lb for 600 hp of mechanical extraction: a difference of 1532 lb. It is further pertinent in the typical operation of a commercial transport aircraft that the altitude and engine thrust are changed as a function of the fuel-burn to yield a maximum range (maximum nautical miles/pound of fuel). Thus as the altitude increases, and the engine thrust settings decrease en route, the SFCs are further exacerbated by the constant bleed airflow rate demand at the engines' lower-power settings and lower core flows.

Engine Production Design

While the bleed air demand impacts adversely on the engine's fuel consumption and its aerothermodynamic design, the reduction in the mechanical complexity of the engine/powerplant (incident upon the removal of the bleed ports, bleed port hardware, blowout doors, etc.) stands as the other major advantage of eliminating bleed air. In the NASA/Lockheed study, for example, there was a weight saving of 1300 lb (in three engines) and a saving of 2540 lb when the stainless steel power ducting was removed from the engines, pylons, wings, and empennage. Clearly, this simplification of the powerplant results in a reduction in the time it takes to install and remove the engine.

Another physical design impact of engine bleed is the precooler installation, which, aside from its weight, results in a crowding of the space in the pylon and a complication to the powerplant (see Fig. 2 view of the Pratt & Whitney JT9D-74 engine). Since the primary function of the precooler installation is to limit the temperature of the discharge air from the cooler to some 500°F, during hot day takeoff/climb conditions, it is redundant at high-altitude cruise conditions. Also, during the climb itself, there is a fuel penalty for the fan bypass air which is used for the precooler. Handling the precooler discharge air through registers on top of the powerplant is another design aspect and problem of the precooler installation. A final consideration in the production design of the advanced technology engine is the interfacing of the bleed ducts (and hardware) with the decreasing dimensions of the final stages of the compressor.

Engine Performance

While the engine designer will welcome the opportunity of not responding to the customer bleed requirements, the engine cycle must be optimized with respect to the potentially higher levels of mechanical power extraction. Rematching of the compressor and turbine must therefore be accomplished to preserve the engine's stability margin over the complete operating environment of the engine. Paradoxically, while engine bleed is antithetical to many engine design aspects, it does increase the stability margin, while mechanical power extraction tends to decrease it. Figure 3a illustrates the typical stability margin between the steady-state operating line and the surge line, while Fig. 3b shows the migration of these lines incident on bleed and shaft-power extraction. To preserve stability, the engine designer may downmatch the compressor (by increasing the turbine vane area) or he may raise the surge line (by modifying the compressor design). The latter technique could, however, result in adding more compressor stages and/or increasing the variable geometry. Clearly, there are penalties to this, but as engine design moves towards full electronic control, it is expected that the preservation of the stability margins by means of variable geometry will be more effectively implemented by electronic control.

Another performance problem is the impact of engine bleed upon the engine's temperature rating during takeoff and

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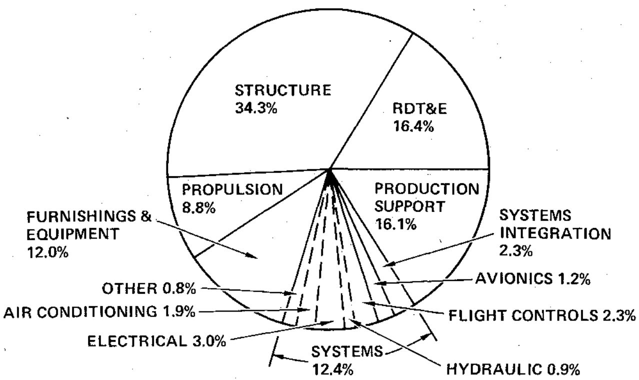

Fig. 1 Conventional aircraft: cost breakdown.

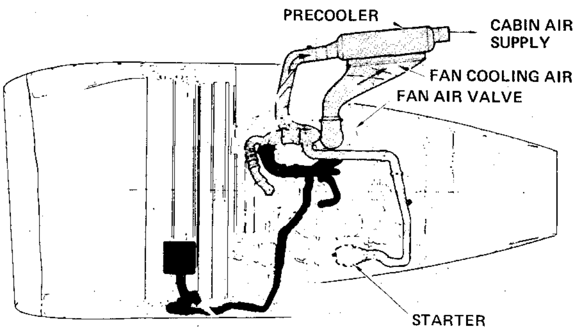

Fig. 2 Pratt & Whitney JT9D-7RN powerplant (left-side view).

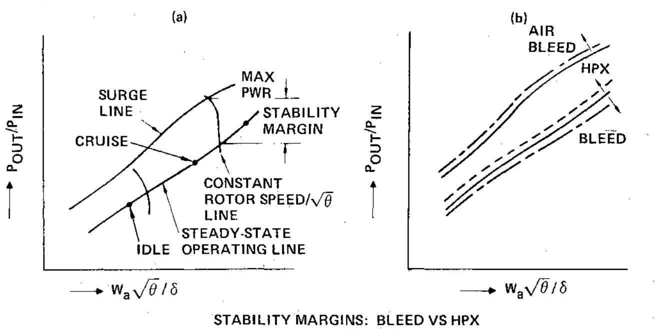

Fig. 3 Advanced technology engines: stability margins.

climb. Typically, the temperature margins (between takeoff and maximum climb) for the E^3 powerplants tend to be less than for the typical bypass engines. For example, the high-pressure turbine of the E^3 is flat-rated to maximum temperature of 2450° F during takeoff and 2345° F during maximum climb. This compares to about 2450 and 2290° F, respectively, for the CF6-50E engine corresponding of a ΔT difference of approximately 105 vs 160° F for the two types of engine.

In the case of a twin-engine transport, a failure of one engine during a hot day climb can cause the turbine inlet temperature to rise above the maximum flat-rated temperature limit. In assessing this situation (in a 150-passenger advanced transport aircraft, using two GE 25,200 lb thrust energy efficient engines) the engine deck identified a ΔT of about 113° F in the remaining engine [with bleed plus horsepower extraction (hpx)] vs only +13° F with (electric) hpx only. The ensuing thrust loss, $-F_n$ on the remaining engine (with the conventional power extraction) was about 12.8%, resulting in a need to resize the engine, with a 16% weight penalty. Similar resizing problems are manifest during idle descent letdown conditions (or during a 22,000-ft hold condition), when the anti-icing and the ECS bleed demand approach an unacceptably high 40% of total core airflow.

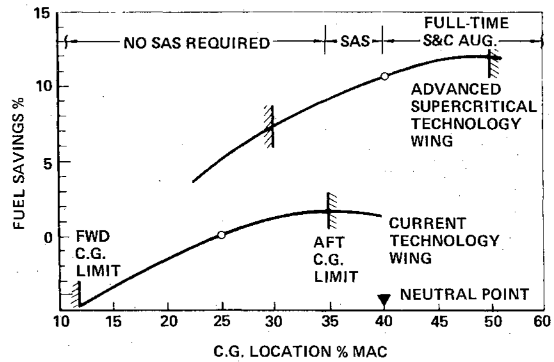

Fig. 4 Fuel savings vs c.g. position: advanced and conventional wings.

Electric Flight Controls

Fly-by-Wire

All-electric flight controls are the key to the full maturation of the all-electric airplane, but it is likely that the implementation of a full fly-by-wire (FBW), power-by-wire (PBW) system will not be accepted (in the commercial application at least) until millions of hours of iron-bird and flight testing have been successfully accomplished. Fortunately, there is now a significant heritage of experience in FBW on a number of military aircraft, and so the technical risk of FBW may be considered low.

Early FBW applications were in the F-4, F-111, YF-12A and spacecraft, while the Anglo-French Concorde was the first commercial aircraft to use electric data control. In the commercial subsonic aircraft, the Lockheed L-1011 incorporated an analog automatic flight control system (AFCS) in 1972 and a digital AFCS (with active controls) early in 1981. The digital FBW systems started with the Apollo in the late 1960s and are now in production aircraft such as the F16 and F18. Digital FBW systems may therefore be considered to be a relatively low technical risk at this time, but there is not yet a flight-ready system (for the commercial application) that meets the reliability criterion of not more than 10^{-9} failures per flight.

In the All-Electric Airplane Study completed for NASA, Lockheed identified a major simplification of the flight control system when the conventional mechanical control system of an L-1011-type airplane was replaced with a quad redundant FBW system. Control of the roll axis alone is most complex since, in addition to two actuators per outboard aileron and three actuators/inboard aileron, there are six modulating spoilers on each wing. Pertinently, the more complex the flight control system, the more it falls into the world of electronic control, since sophisticated programming functions can be readily implemented via the flight control computers. Viability and ease of changing transfer functions therefore stand as the major benefits of all-electrical flight control along with other benefits such as reduced weight, reduced maintenance/rigging time, and simpler production installations.

The prospective fuel savings are another projected benefit when FBW is adapted to advanced technology wings. The lower curve of Fig. 4 shows that as the c.g. travels aft from 25 to 35% there is an approximate 1.5% fuel saving, due to reduced trim drag. For the advanced (supercritical) wing design, a 40% (neutral) c.g. position yields an approximate 11% fuel saving, but stability augmentation is required between 34 and 40%. Further movement of the c.g. toward 50% yields another fuel saving, but the airplane becomes longitudinally unstable, so a full-time pitch-stability augmentation system is necessary. Operating the airplane in the regime of relaxed or negative static stability evidently requires full-time electronics, but it can add to the other projected fuel savings of the all-electric airplane.

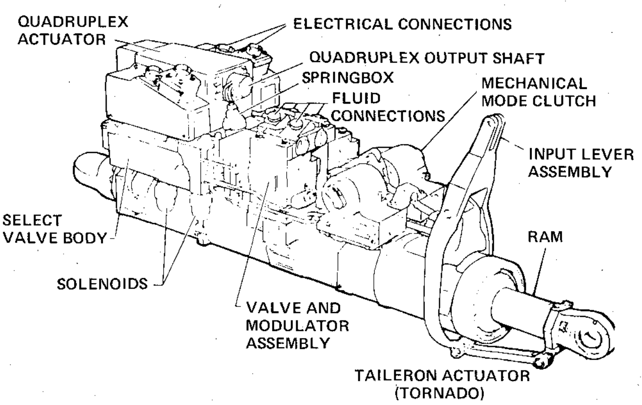

Fig. 5 FBW/hydraulic actuator: MRCA (Fairey Aircraft).

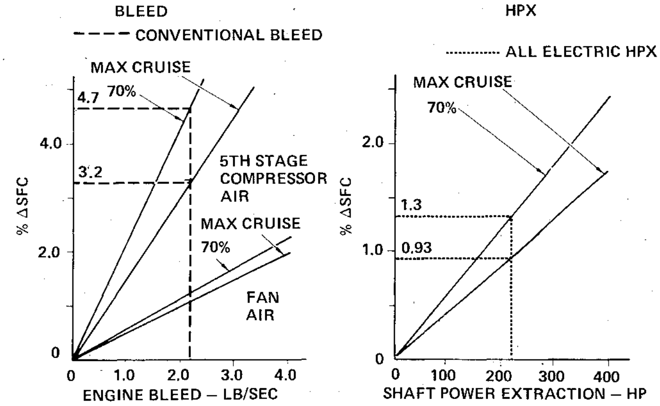

Fig. 7 Pratt & Whitney E^3 technology: ΔSFC penalties (bleed vs hpx).

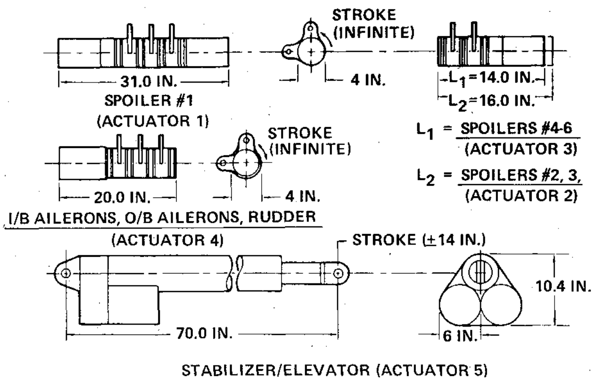

Fig. 6 500-passenger ATA: electric FCS actuators (AiResearch).

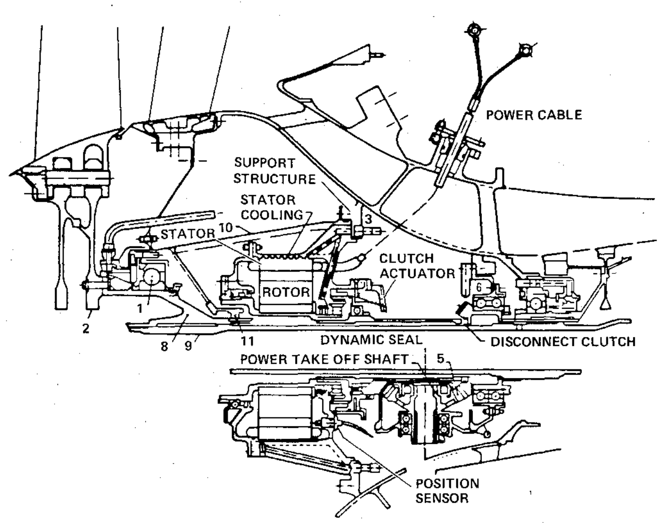

Fig. 8 SmCo integrated engine generator starter (General Electric).

In high-performance military aircraft today, the trend is to take advantage of integrated electrohydraulics, wherein quad redundant FBW technology is directly interfaced with the hydraulic actuation. Figure 5 shows such a Fairey actuator used for the ailerons in the multirole combat aircraft (MRCA). A further extension of the technology is exemplified by the use of a triredundant fly-by-light (FBL) system with a hydraulic actuation, as accomplished by the Bertea Company.

Power-by-Wire

The further extension of the flight control system (FCS) technology is a FBW/power by wire (PBW) system in which the hydraulic-mechanical actuation system (HMAS) is replaced with an electromechanical actuation system (EMAS). A high level of expertise currently resides in the design of electromechanical actuators, since their utilization in missiles and nonprimary control surfaces in aircraft goes back over 30 yr. Most recently, however, with the proliferating growth in power electronics (and the emergence of the rare Earth permanent magnet materials), there is now a trend toward the use of samarium cobalt (SmCo) motor-actuators for primary flight controls. SmCo motors are not only highly efficient and reliable, but their power/weight ratio can be termed a technology breakthrough. For example, a SmCo motor designed for a torpedo propulsion system develops 145 hp and weighs only 35 lb. It is on such new technology that an all electric FCS is primarily based, but there are other EMAS candidates, such as the highly reliable squirrel-cage induction motor (interfaced with a power hinge or differential toroidal drive), that compete with the SmCo drives.

Looking at the production installation of a FBW/PBW system vs a conventional mechanical/HMAS FCS, it is clear again that a major simplification ensues. This derives mainly from the fact that rotary electric actuators permit the surfaces to be actuated along their hinge line, as opposed to linear (hydraulic) actuators which, in some cases, result in a penetration of the spar beam. Also, high-pressure hydraulic lines are eliminated in the all-electric FCS, so the problems of leakage at in-line joints, contamination, and fire hazards are also eliminated.

To evaluate real-world conditions in the NASA/Lockheed study, a large 500-passenger transcontinental advanced transport aircraft (ATA) was selected as the baseline for the all-electric FCS. A total of 29 actuators were designed for this ATA (by AiResearch) and all were rotary with the exception of the four linear actuators on the horizontal stabilizer. These actuators (Fig. 6) were designed to meet the same hinge moments, surface control rates, frequency/bandwidth response, overall servo stiffness, and other performance characteristics of the L-1011 hydraulic actuators. In the system proposed, quad digital flight control computers (designed by Honeywell) transmitted a multiplexed digital bit-stream (in response to flight station commands), to electronic assemblies which powered the SmCo motor-actuator in a closed-loop servo control.

From the weight analysis and trade of the mechanical/HMAS vs the FBW/PBW, an uncycled weight saving of nearly 1200 lb was identified in the 500-passenger ATA. To some extent, this was conservative, since in the NASA/Lockheed study, a 630-lb weight penalty was assigned to the electric actuator (1430 vs 800 lb). Later weight projections now indicate that advanced SmCo actuator designs could be competitive and prospectively lighter than their hydraulic counterparts. For example, Boeing in their one-for-one replacement of hydraulic actuators in the quiet short-haul research aircraft (QSRA) with electric actuators, found that the electric actuators were actually lower in weight.

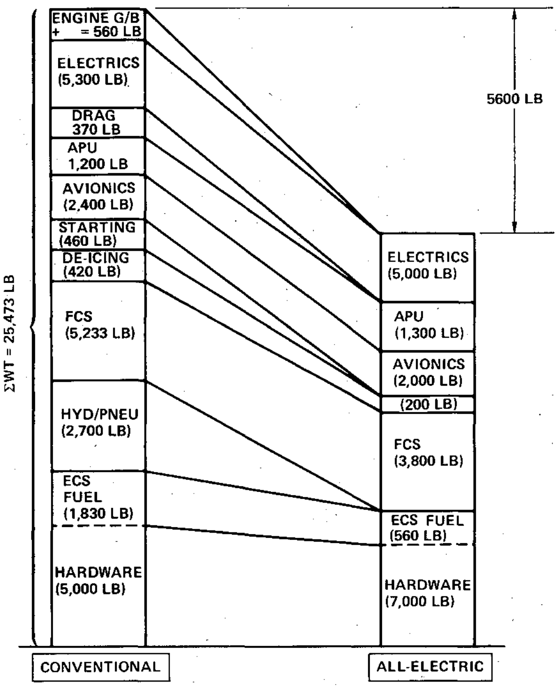

Fig. 9 ATA 500-passenger weights: all electric vs conventional.

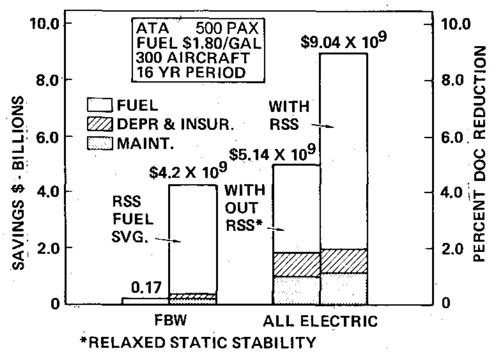

Fig. 10 ATA 500-passenger costs/DOC savings (all electric).

Environmental Control System

This is a major system in any commercial or military aircraft. In the high-performance military aircraft, however, the objective is not so much the control of the human environment as the cooling and thermal management of the sophisticated avionic equipment. Nonetheless, the large military transport and large commercial transport both derive major benefits in terms of performance, production, and maintenance support costs. For example, Fig. 7 shows that a 2.16-pps fifth-stage bleed on the Pratt & Whitney E^3 design increases the SFC 3.2%, while a shaft power extraction of 216 hpx exacts only a 0.93% fuel penalty: this penalty is actually conservative, since a more typical lower power setting would further increase the bleed air fuel penalty.

The ECS is another labor-intensive system since a significant amount of customized stainless steel ducting is routed from the engines and the auxiliary power unit (APU) to the fuselage distribution ducting. The major production gain in the all-electric airplane is therefore in the elimination of all the power ducting and the associated control valves/mounting hardware in the engine, etc. The stainless steel splitter that encloses the ducting in the powerplant could also be eliminated or be made of composite material. Excluding any weight saving in the splitter assembly, some 2540 lb of ducting were eliminated in the 500-passenger ATA.

In replacing a bleed air powered ECS with an all-electric ECS (AEECS), cabin pressurization must be achieved through the use of dedicated motor-driven compressors. Cooling could be likewise implemented with a motor-driven bootstrap, or motor-driven Freon-compressor system; the latter was chosen in the 500-passenger ATA design. While engine bleed out elimination is a major objective, the other main advantages of the all-electric ECS are that the electric-turbomachinery can be conveniently located in a below-floor fuselage compartment, and the airlines do not have to provide pressurized, or conditioned, air at each of the gates.

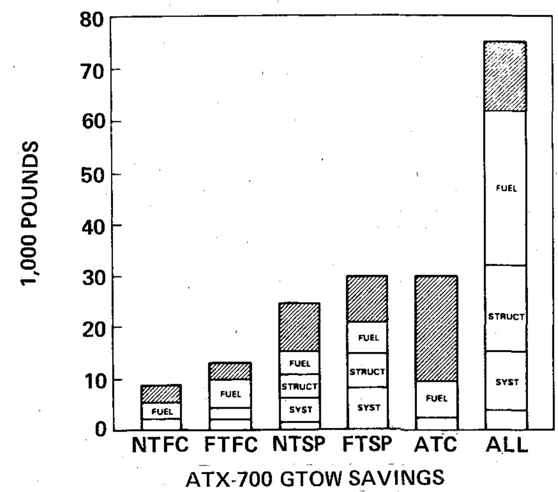

Fig. 11 ATA 700-passenger weight savings (all electric).

Finally, it is of note that the AEECS plays a major role in sizing the electric power system inasmuch as it places its capacity at a much higher level than conventional power systems, which are typically 60/75 kVA. In the 500-passenger ATA, a 300-kVA capacity (configured with two 150-kVA generators per powerplant) was determined necessary to meet the engine-start requirement and the various electric loads. The ECS itself presented a major demand on this electric power capacity in that it required some 500 hp for cabin pressurization alone.

Hydraulic System

The production installation of high-pressure hydraulics ranks as one of the most labor-intensive systems in modern aircraft. Currently, while most aircraft use 3000-psi systems, the North-American Rockwell B-1 airplane uses a 4000-psi system and consideration is now being given to 8000-psi systems as in the case of the studies on the F-14 airplane. The 8000-psi systems are being considered primarily for the prospective weight and cost savings, but these systems will require the most detailed quality control methods to avoid line/joint failures and seepage problems at the line/joints, etc. In previous weight studies of the conventional 3000-psi system in commercial aircraft, titanium lines and titanium housings were found to offer attractive weight saving over the steel pressure lines and aluminum return/suction lines.

Physically, the hydraulic installation is a major undertaking and, in a large ATA, it takes on significant proportions. Some eleven different fluid power sources are typically involved, and these are interfaced with filters, reservoirs, valves, regulators, and a very large number of hydraulic lines with mechanical/welded in-line joints. Leakage, noise, and contamination are some of the problems of hydraulics, and their elimination (or mitigation) adds further to the design/installation complexity. In a wide-body jet aircraft the following statistics are typical:

1) number of tubes: steel—800; aluminum—420
2) number of welds: bench—1000; ship—300
3) swaged fittings: tubes—1800, component adapters—800
4) hydraulic lines: 5000 ft.

In the resized large ATA, which used the L1011-500 as the baseline, an uncycled weight saving of 2700 lb was identified with the elimination of the hydraulic system in the all-electric airplane. In the elimination of the hydraulic system, it was of course necessary to employ EMAS for those services and functions performed by hydraulics in the conventional airplane.

Engine Starting

To a major degree, the new (electric) engine-starting technology is a result and outgrowth of the many forward-looking U.S. Air Force/AFWAL programs. It is also worthy of note that there is a synergistic relationship between the ECS power requirement and the engine-start requirement. In the case of the large ATA studied, the selection of two 150-kVA generator/powerplant was influenced mainly by the ECS, but, as a consequence, it was possible also to start the 46,000-lb thrust engines with these generators. Simulated starter-generator tests have been completed on RB211-type engines, and actual tests on engines such as the TF-34 (used in the A10 and 5-3 airplanes).

For the production engineering relevance, a SmCo machine used in the dual role of a generator and a starter means that the conventional pneumatic starter installation can be completely eliminated. Indeed, it would be counterproductive to eliminate the high temperature ducting associated with the ECS, only to reinstate it again for a pneumatic engine-start system. Thus it is essential to provide an electric start system in the all-electric airplane.

In evaluating the benefits of eliminating the pneumatic start system, the primary advantages are in removing the pneumatic starter and the valves/ducting in the powerplant. Typically, when the pneumatic starter is located at the 6 o' clock position, it results in a ballooning of the lower contour of the engine nacelle and an increased drag. As the generator doubles as a starter, there is no need for a separate dedicated electric starter motor (or additional wiring), but two static power inverters were added to furnish the electric power during starting. Either one of these inverters could start the engines when they are connected to external power or the onboard APU.

Electric Power System

The following five systems are typical candidates for the AEA:

1) Advanced CSDG as (constant speed drive/generator)
2) VSCF (variable speed/constant frequency) —cycloconversion
3) VSCF—dc link
4) 270 Vdc
5) VV/VF (variable voltage/variable frequency).

All of the above systems, with the exception of system 1, are all electric methods of power generation. In the CSD generator system, the drive is a sophisticated hydromechanical transmission whose function is to maintain a constant output speed when the engine input speed varies over a 2:1 or more speed range.

The most highly developed of the VSCF power systems is the cycloconverter system in which the variable voltage/variable frequency (VV/VF) output of the generator is converted to constant voltage/constant frequency (CV/CF) by static power electronics. Being a cycloconverter (ac-to-ac) system, a high frequency of some 3 to 4 times the output frequency (400 Hz) is required and from the lower 400-Hz sine wave is derived or synthesized. This system is in use on the A-4D, F-18 aircraft and was recently selected for starter/generator testing in the A-10 aircraft.

The VSCF dc link also takes VV/VF power from the variable speed generator, but in this case the power is rectified to dc and then inverted, by power electronics, to CV/CF ac. This system does not have the background and development experience of the VSCF cycloconverter system, and it is currently limited (by the power ratings of the transistors) to capacities of 40 to 60 kVA. The dc link system does, however, have the advantage that it does not require a generator with a large number of poles and it does not have to be run at very high speeds. It is therefore possible with the dc link approach to generate fairly conventional frequencies and then invert to ac. This system has had a significant amount of laboratory testing, and the first production aircraft application will be the F-5G aircraft.

The 270-Vdc system is primarily a Naval Air Development Center (NADC) development. In this case, all the VV/VF generator power is rectified to 270 Vdc (inside the generator) and then, as far as possible, is utilized directly by loads such as avionics. Other power is inverted to three-phase 200 V 400 Hz ac for typical ac equipment, while other inverters synthesize ac power for SmCo-type motors. There is currently no production aircraft application of the 270-Vdc system.

The operation of the VV/VF system is somewhat antithetical to the 270-Vdc systems. It utilizes ac power directly (for loads such as wing/engine deicing, heating, lighting, galley loads, ac induction motors), and it then converts the smaller percentage to 270 Vdc and three-phase 200 V 400 Hz CV/CF ac. Again, there is no production experience in this system, but it was selected as the simplest and most efficient system for the all-electric airplane in the NASA/Lockheed study. It is of note here that with the trend in the AEA, the large capacity generators must operate with a very high transmission efficiency to avoid undesirable electrothermal management problems. For example, if 300 kVA (at a 0.85 power factor) is delivered to an ac distribution bus at an efficiency of 0.72, the heat dissipation would be $300 \times 0.85 (1/0.72 - 1) = 99.16$ kW = 5652 Btu/min. For the VV/VF system, with a transmission efficiency of 0.92, the heat dissipation would be only 1264 Btu/min.

In the final analysis, when the concept of the AEA is implemented by the engine suppliers, the fuel and lube pumps will be also driven electrically. When this is done it will be possible to consider the direct mounting of the generator rotor(s) over the high-pressure spool shaft, as shown in Fig. 8. Such an integrated engine generator/starter (IEG/S) development has been pursued by General Electric under AFWAL contracts. The production advantages of this novel approach are self-evident, since the engine will come complete with output electrical terminals!

Technology Benefits of AEA

The all-electric airplane has the potential for yielding major production, operational, and life cycle cost benefits over the conventional airplane. Two of the more quantifiable benefits are the prospective weight savings (which are significant) and the reduction in the direct operating costs (DOC), which for the commercial airline operator is the bottom line. Figure 9 shows a significant 5600-lb (uncycled) weight saving in a 500-passenger ATA with an operating empty weight (OEW) of 242,000 lb. When this weight was cycled back using the Lockheed's Aircraft Systems Synthesis and Evaluation Technique, ASSET (to determine the changes in structural, engine, fuel weights, and changes in the aerodynamic/engine performance), the takeoff gross weight (TOGW) savings were a significant 25,500 lb.

Costs were the other significant parameter of interest and here again results were impressive. For example, the payoffs for a 300 airplane market with a 16-yr life, and fuel costs at \$1.80/gal, were a dramatic savings of \$5.13 billion and a 5% reduction in DOC. If the fuel saving, from operating the aircraft with relaxed static stability, is added, the total saving increases to \$9.04 billion and the DOC reduction is approximately 9% (see Fig. 10).

In a later study,[2] similar salutary results were revealed for 150-, 350-, and 700-passenger airplanes. For example, Fig. 11 shows a potential TOGW weight saving of some 62,000 lb, or about 76,000 lb, if other advanced technologies, (such as powered wheels and other new technologies) are implemented; these latter technologies are represented by the cross-hatched sections. Figure 11 is also more definitive in that it breaks down the weight savings in fuel, structure, etc., for the near-time flight controls (NTFC) and for far-term secondary power (FTSP), etc.

Conclusions

The transition from the conventional to the all-electric airplane will undoubtedly be evolutionary and its rate will be determined by degree of commitment to the concept. Certainly with the dedicated support of NASA, the military, and the engine/airframe supplier industry, the development time frame can be shortened. The incentive for an enthusiastic endorsement of the all-electric airplane will also be influenced by a favorable perception of the real payoff in terms of productivity, aircraft availability, producibility, total cost, and the logistic/maintenance support aspects.

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[2]Howison, W.W. and Cronin, M.J., "Electronic/Electric Technology Benefits Study," NASA-LRC/Lockheed NAS-16199, Jan. 1982.